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A REVIEW ON THE ROTARY ULTRASONIC MACHINING OF ADVANCED CERAMICS

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ABSTRACT

Advanced ceramics are likely candidates for many industrial applications due to their superior properties. However, their high machining costs lead to limited applications. Rotary ultrasonic machining (RUM) is one of the cost-effective machining processes available for drilling holes in advanced ceramics. This paper reports on investigations in the last few years on RUM process of advanced ceramics. Emphasis is given on the effect of RUM process parameters (such as applied static load, rotational speed, ultrasonic power and vibration amplitude, abrasive grit size and coolant) on machinability parameters (such as material removal rate, tool wear and surface roughness). Results on tool wear and edge chipping are also reported.

Keywords: *Rotary Ultrasonic Machining, ceramic, edge chipping, material removal rate*

1.0 INTRODUCTION

Advanced ceramics are likely candidates for many industrial applications because of their superior properties, such as chemical inertness, high hardness and wear resistance, high strength and stiffness at elevated temperatures, high strength-to-weight ratio, corrosion resistance, and oxidation resistance [1,2]. However, advanced ceramics are difficult to be machined into desired shapes and dimensions due to their high hardness, non-electrical conductivity and brittleness

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[2]. It was reported that the machining cost for ceramic components could be as high as 90% of the total cost [3].

Ultrasonic machining (USM) is considered as “probably the most frequently used machining method for advanced ceramics” besides grinding [3]. Figure 1 shows a schematic illustration of USM. USM accomplishes the removal of material by the abrasive action of a grit-loaded slurry, circulating between the workpiece and a tool that is vibrated at small amplitude and high frequency. However, the poor abrasive slurry flow in drilling deep holes, low material removal rate due to abrasive slurry, low accuracy in drilling small holes and considerable tool wear preclude wider application of USM [4-6].

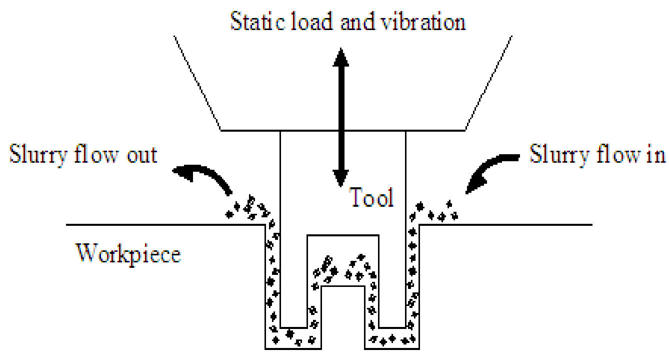


Figure 1: Schematic illustration of ultrasonic machining

Rotary ultrasonic machining (RUM) is one of the cost-effective machining processes available for drilling holes in advanced ceramics. RUM is a hybrid machining process that combines the material removal mechanisms of diamond grinding and USM, resulting in higher material removal rate (MRR) than that obtained by either diamond grinding or USM [1]. RUM also gives superior surface finish, improved hole accuracy, capability to drill deep holes and low tool pressure [7]. Figure 2 is a schematic illustration of RUM. A core drill tool with metal-bonded diamond abrasives in rotational motion, ultrasonically vibrated simultaneously, is fed towards the workpiece at a constant feedrate or constant force (pressure). Coolant is pumped through the core of the drill in order to wash away the debris, prevent jamming of drill tool and keep both drill and workpiece cool.

2.0 EFFECT OF CONTROL VARIABLES ON RUM DRILLING PERFORMANCE

This paper is aimed to review the effects of RUM process parameters (such as rotational speed, applied static load, ultrasonic vibration amplitude, etc.) on the RUM performances (such as MRR, tool wear, surface roughness or hole clearance) of advanced ceramics, based on previous experiments done by other researchers.

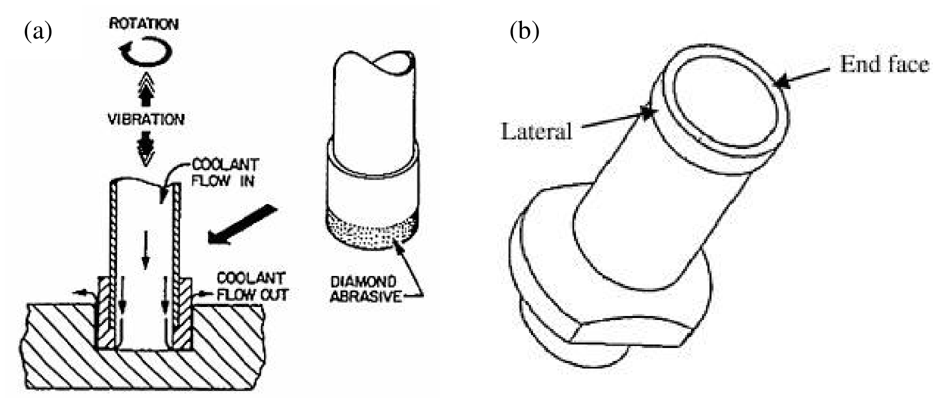


Figure 2: Schematic illustration of rotary ultrasonic machining
(a) RUM process (b) 3D view of the RUM tool [8]

2.1 Effect of Static Force (Pressure)

The static force has remarkable effect on RUM drilling performance. For advanced ceramic materials like magnesium stabilized zirconia and alumina, as the static force increases, material removal rate will increase (see Figures 3 and 4). From Figure 3(a), it is noted that the MRR was seen to decrease at the highest value of the static load. Zhang et al. [9] explained that higher loads will decrease the amplitude of tool tip vibration and will prolong the contact time, and if the force is excessive, the tool cannot vibrate properly and swarf cannot be flushed away effectively, thus resulting in a decrease in MRR. For ceramic matrix composite like C/SiC , as the static force increases, MRR will increase (see Figures 5(a) and (b)); and hole clearance will decrease (see Figures 5 (c) and (d)).

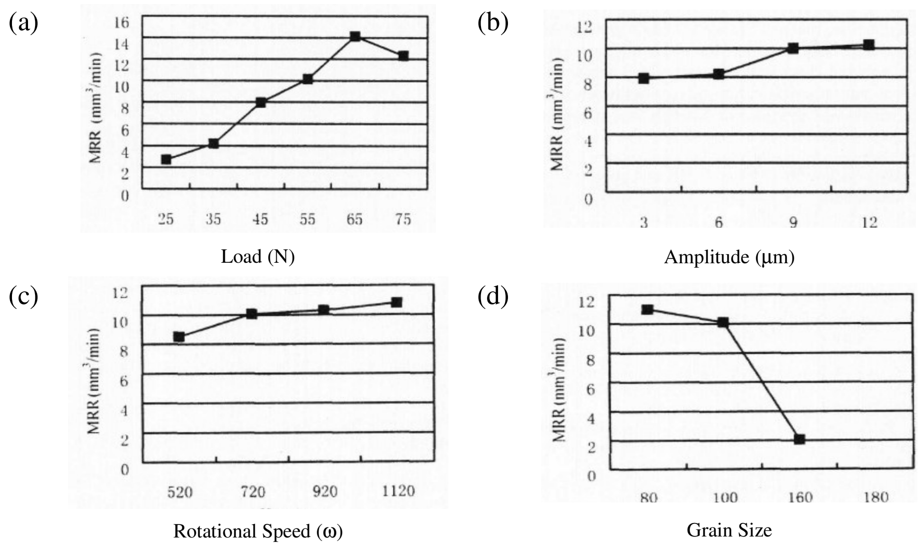


Figure 3: Effect of control variables on material removal rate of alumina [9]

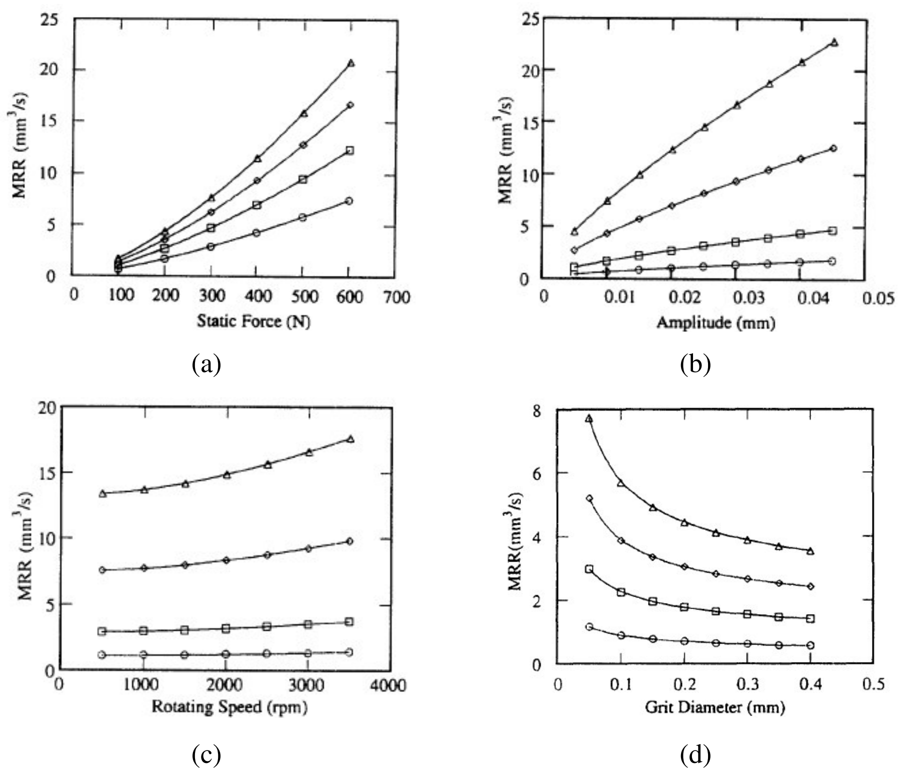


Figure 4: Effect of control variables on material removal rate of magnesium stabilized zirconia [10]

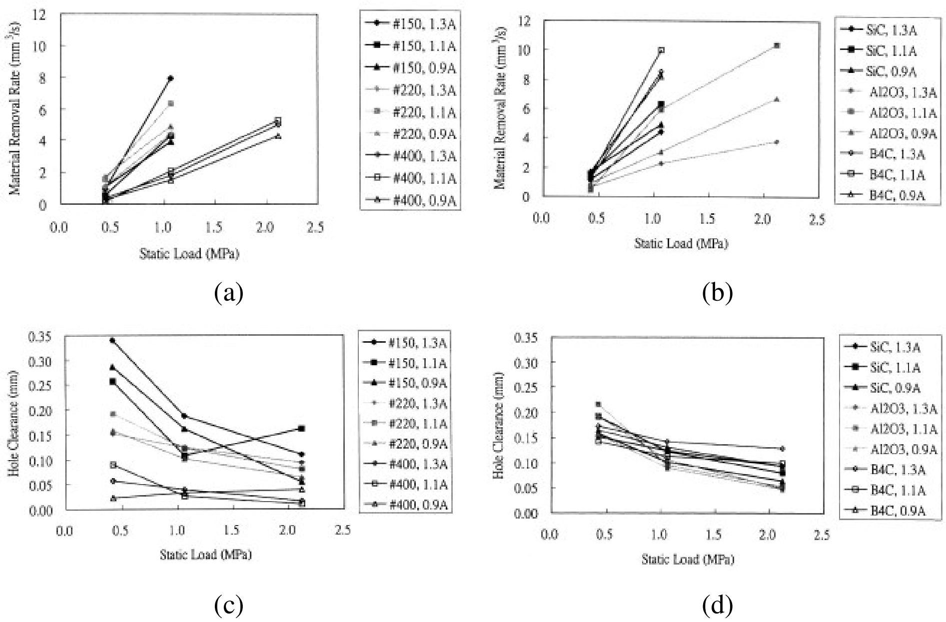


Figure 5: Effect of static pressure on RUM of C/SiC [11]

2.2 Effect of Ultrasonic Power and Vibration (Amplitude and Frequency)

For advanced ceramics, the MRR tends to increase with an increase in the amplitude of tool vibration as shown in Figures 3(b) and 4(b). For C/SiC composites, the optimal vibration amplitude (determined by electric current) produces the maximum MRR (see Figures 5(a) and 5(b)) and the hole clearance increases as the vibration amplitude increases (see Figures 5(c) and 5(d)). Meanwhile, the MRR increases as the vibration amplitude goes up to a certain value and declines thereafter, as shown in Figure 6(a). The trends of vibration amplitude on tool wear and surface roughness are shown in Figures 6(b) and 6(c).

Large amplitude of tool vibration not only results in a large dynamic force on the workpiece but also leads to more effective flushing away of debris. Both of these have a positive effect on material removal, thus the MRR increases with the amplitude of tool vibration [9]. The reduction in MRR could be attributed to “an excessive increase in alteration loading on the diamond grits and a weakening of the bond” [12].

There are limited literatures reported on the effect of vibration frequency on RUM performance. Generally high vibration frequencies (usually ≥ 20 kHz) are used in the reported experiments. Figures 6(d) to 6(f) show the trend of vibration frequency on MRR, tool wear and surface roughness.

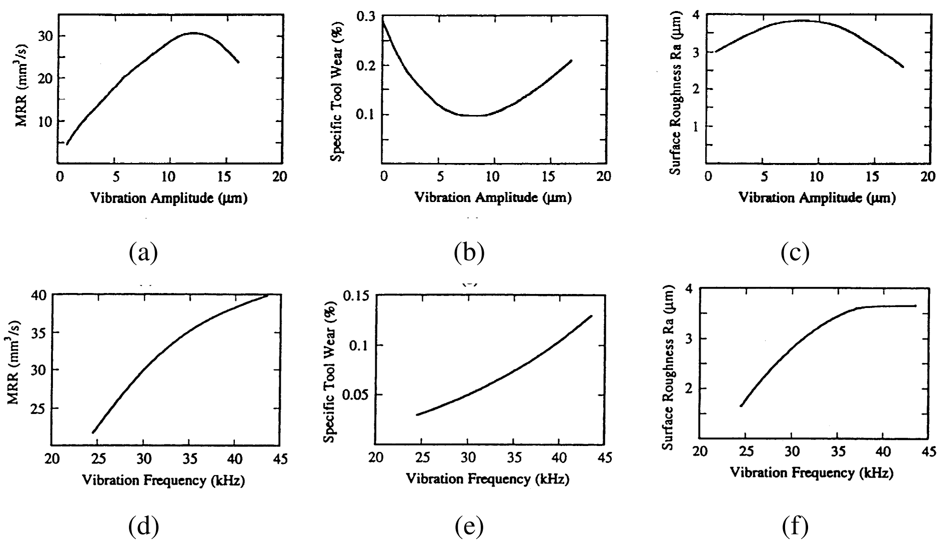


Figure 6: Effect of ultrasonic vibration on RUM of ceramics [13]

The relationship between the vibration amplitude and the drilling force for various ceramics and soda-glass is shown in Figure 7. The plots at amplitude zero indicate the force in conventional core drilling. It shows that a significant reduction of drilling force can be achieved when ultrasonic vibration is applied [2].

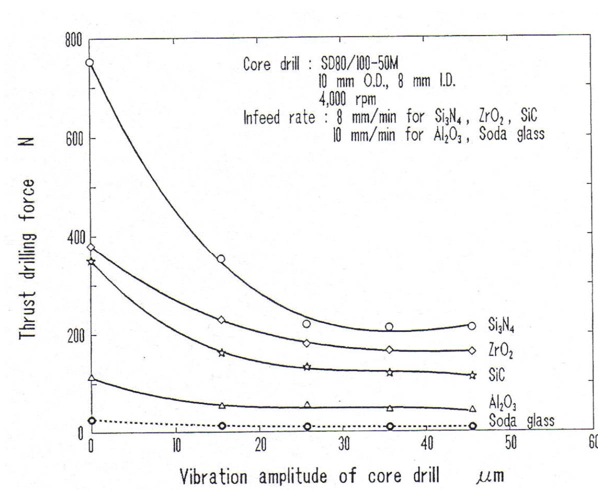


Figure 7: Effect of vibration amplitude on cutting force [2]

Li et al. [14] reported that the MRR for RUM would increase with the increase of ultrasonic power. Vibration amplitude is also increased as the ultrasonic power controls the vibration amplitude. As vibration amplitude increases, the cutting depth of each diamond abrasive bonded on the core drill will increase so that MRR for each diamond abrasive will also increase. The increase of MRR for each diamond abrasive will lead to the increase of MRR for the entire RUM process [14].

2.3 Effect of Rotational Speed

Similar tendency of the effect of rotational speed on MRR of RUM could be found in some past reports [9,10,13,14]. The MRR increases when rotational speed is increased but is not increased proportionally. Figure 3(c), Figure 4(c) and Figure 8 show the trend of rotational speed on MRR.

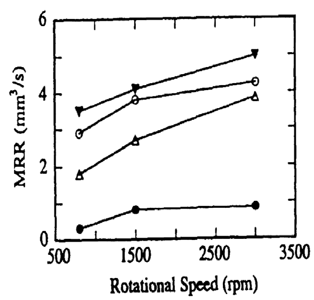
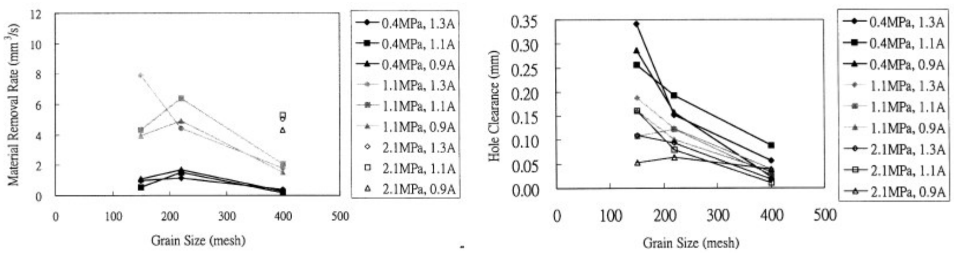


Figure 8: Effect of rotational speed on RUM of ceramics [13]

As the spindle speed increases, the indentation volume changes proportionally and the MRR will increase [14]. Thus, with increased rotational speed more debris is formed and flushing it away becomes increasingly difficult. This will also affect the self-sharpening of abrasive grains which includes two components, progressive abrasive grain fragmentation and progressive bond erosion [9]. When the swarf is not perfectly flushed away, bond erosion and abrasive grain fragmentation become difficult, resulting in the dulling of drilling tool, thus affecting the MRR that will not increase proportionally [9].

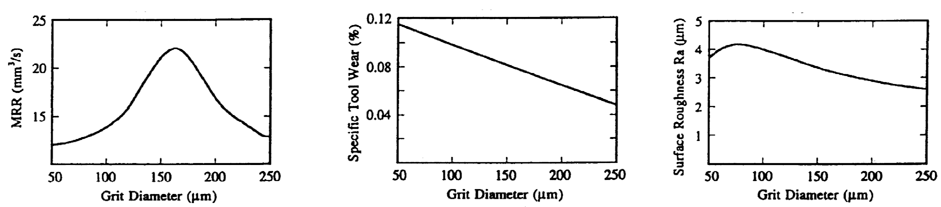
2.4 Effect of Abrasive Grit Size

Many papers have reported the effects of abrasive on RUM drilling performace. Figures 3(d) and 4(d) show similar trend of MRR as the increase of abrasive grit size. Figures 9(a) and 10(a) show that MRR will increase as the abrasive grit size increases to an optimal value of abrasive grit size, and decrease thereafter. It has been reported that the optimal value depends upon the amplitude of the tool oscillation [15]. The MRR increases because the coarser abrasives cause more damage of material during the hammering of abrasives [11]. However, the MRR then decreases because the actual amount of abrasive particles is reduced when the size of the abrasives is increased at the same level of slurry concentration [11].



(a) (b)

Figure 9: Effect of abrasive grit size on RUM of C/SiC [11]



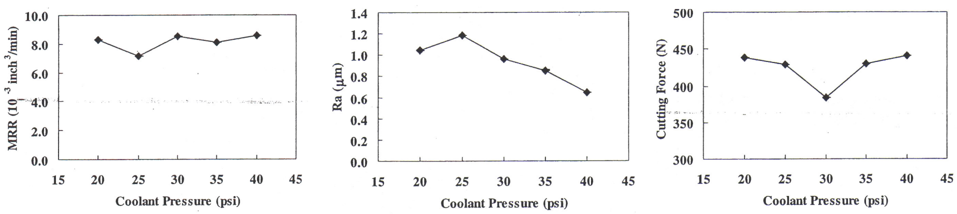
(a) (b) (c)

Figure 10: Effect of abrasive grit size on RUM of ceramics [13]

Figure 10(b) shows the effect of abrasive grit size on tool wear. Figures 9(b) and 10(c) show the effect of abrasive grit size on hole clearance (surface roughness). The hole clearance increases as the abrasive grit size increases. Similar results can be found in the literatures [9,10].

2.5 Effect of Coolant

Effect of coolant pressure and coolant type has been reported [16]. Figure 11 shows the effect of coolant pressure on MRR, surface roughness and cutting force. Figure 11(a) shows that coolant pressure has no significant effect on MRR within the tested range. Surface roughness increases until the coolant pressure reach 25 psi and declines thereafter (see Figure 11(b)). The lowest cutting force is obtained at coolant pressure of 30 psi (see Figure 11(c)). Regarding the effect of coolant type, tap water and synthetic coolant provide higher cutting force than water-based coolant. These coolant types have no significant effect on MRR and surface roughness.



(a) (b) (c)

Figure 11: Effect of coolant on RUM of alumina [16]

3.0 TOOL WEAR

In RUM of advanced ceramics, it is difficult to separate diamond grains from grinding debris [8]. Zeng et al. [8] reported that the microscope method was used for investigation into tool wear mechanism in RUM of SiC. A special fixture was designed for holding the tool in order to ensure that the same area of the tool was observed every time. The topography was observed on both the end face and lateral face of the tool.

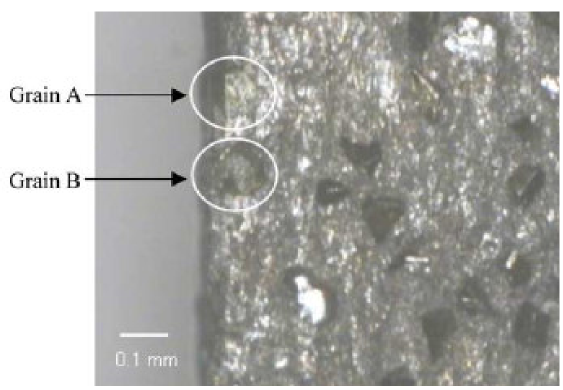


Figure 12: Tool lateral face before drilling test on SiC. Grains A and B were dislodged after 16 drilling tests [8]

3.1 Wear of Tool Lateral Face

Figure 12 shows the tool topography on lateral face before any drilling test was performed. After 16 drilling tests were performed, wear of the diamond grains at the edge of the lateral face (close to the end face) was quite severe. Two diamond grains (grain A and grain B as indicated in Figure 12) at the edge were dislodged after 16 drilling tests [8].

3.2 Wear of Tool End Face

Figures 13 (a) to (c) show the topography of the tool end face before drilling test, after 6 and 16 drilling tests were performed. From Figure 13(b), large wear-flats can be observed on diamond grains. It can be seen that few diamond grains are pulled out during the first 6 drilling tests. Comparing Figures 13(a) and 13(c), it can be observed that most of the diamond grains on the tool end face are pulled out after 16 drilling tests. It shows that the wear of tool end face is so severe that most of diamond grains are dislodged [8].

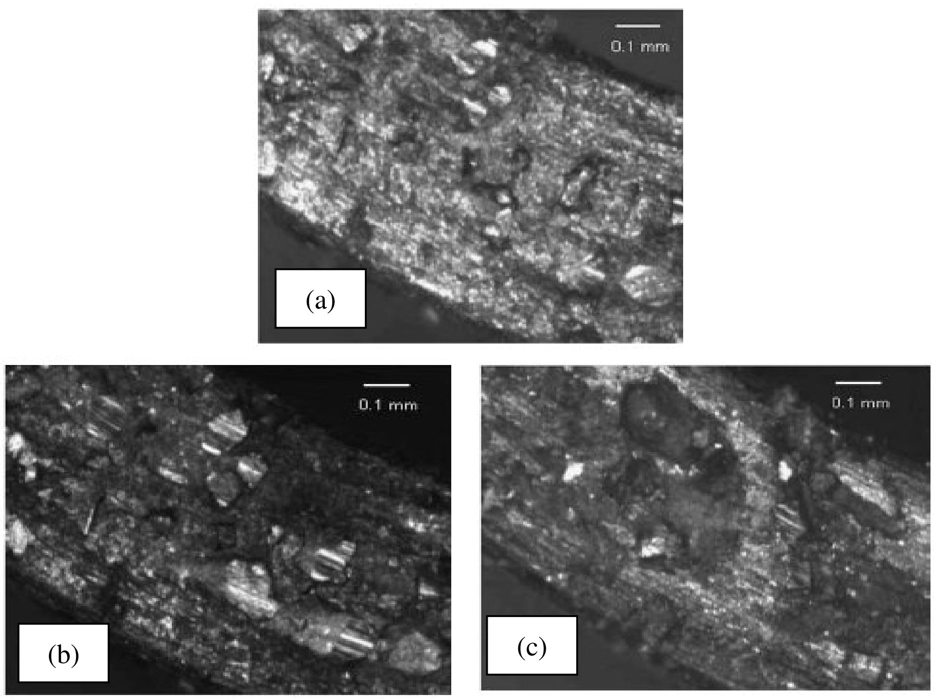


Figure 13: Topography of tool end face (a) Before drilling test on SiC
(b) After 6 drilling tests (c) After 16 drilling tests [8]

It is clearly shown that the diamond grain dislodgment is due to bond fracture in RUM of SiC. Some diamond grains were pulled out of the metal bond prematurely, before completing their effective working lives. A grain completely pulled out of the metal bond results in a hole on the tool end face. Weakening of the interfaces between diamond grains and metal bond may be due to mechanical impact and high temperature [8].

4.0 EDGE CHIPPING

Drilled holes on hard and brittle materials such as advanced ceramics are very different from those on metal workpieces. Chippings are the key barrier of drilling high-quality holes on these hard and brittle materials. Edge chipping (or chamfer) shown in Figures 14 (a) to (d) not only compromises geometry accuracy but also causes possible failure of the component during service [17]. Generally, edge chipping is not acceptable on finished products, and has to be machined off by other processes after the RUM operation. The larger the edge chipping thickness, the higher is the total machining cost [18].

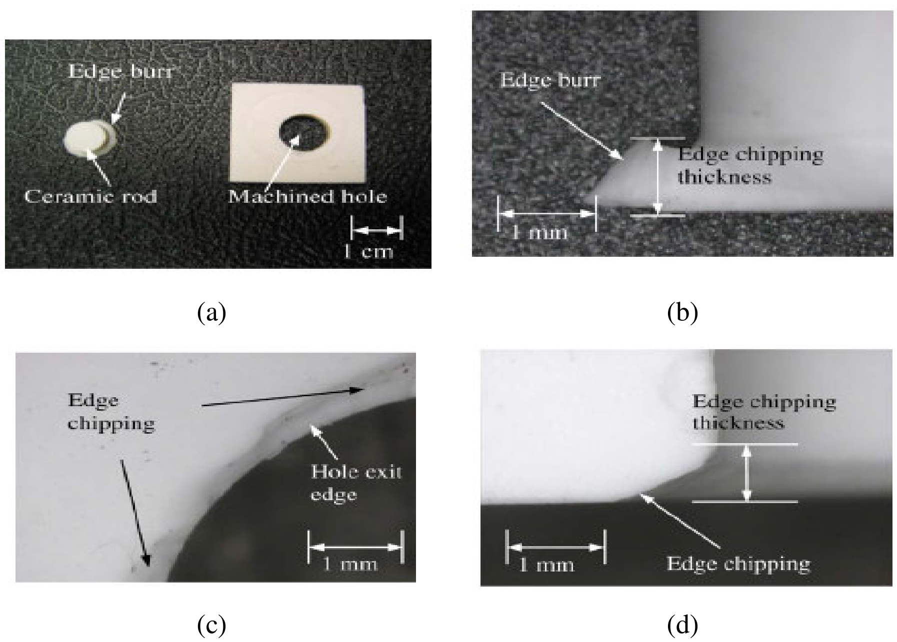


Figure 14: Edge chipping induced by RUM (a) Two parts resulting from RUM (b) Side view of machined rod (c) Bottom view of hole exit (d) Side view of hole exit [18]

Little research on edge chipping in RUM has been reported. Li et al. [14] reported that the main influencing factor on edge chipping was the cutting force, which was determined by the controllable machining variables such as spindle speed, ultrasonic vibration amplitude, and feedrate. They found that the edge-chipping thickness could be reduced by using higher spindle speed and smaller feedrate due to reduced cutting forces.

Li et al. [18] conducted a preliminary study on the initiation of edge chipping in RUM using a three-dimensional (3-D) Finite Element Analysis (FEA) model. Figure 15 shows the boundary conditions and applied loads for the FEA model. They used the von Mises stress failure criterion to predict the edge chipping initiation. From both the simulation and experimental results, they found that the edge chipping thickness could be decreased by increasing the support length. Figure 16 shows the predicted and experimental results for the effects of support length on edge chipping thickness.

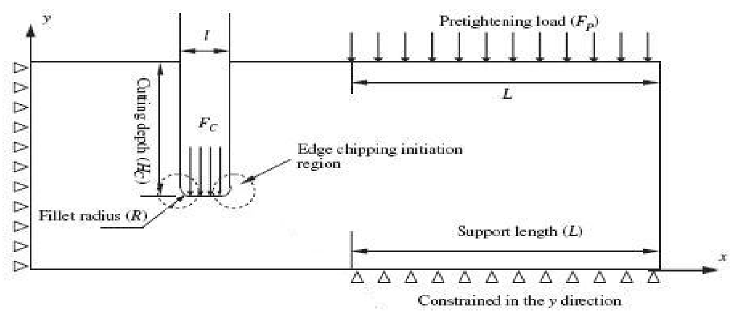


Figure 15: Boundary conditions and applied loads for the FEA model [18]

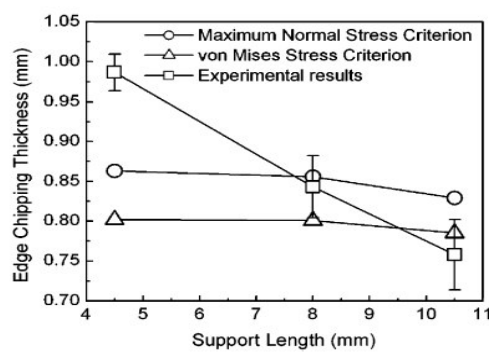


Figure 16: Predicted and experimental results for the effects of support length on edge chipping thickness. (F_C = 3.7 MPa and F_C = 15 MPa for the FEA simulations) [18]

5.0 FUTURE ADVANCEMENT

Some potential future developments and innovations based on literature reviews are summarized as follows:

i) Further investigations on RUM applications, particularly for various hard-to-machine advanced ceramics, technical glass materials and composites, semiconductors, laser rods and fiber optic preforms [7,19,20].
ii) Studies of ductile mode machining and subsurface damages of RUM on hard and brittle materials [20].
iii) Development of dressing technique for RUM tools [20] and extension of RUM for other potential machining applications [7].
iv) Study of RUM on materials that required high machining cost using conventional machining processes such as titanium alloys [21].

6.0 CONCLUSIONS

It can be concluded that the material removal rate increases with increases of applied static load, ultrasonic power and amplitude of tool vibration, rotational speed and grain size. The surface roughness or hole clearance tends to increase with the increase of vibration amplitude and abrasive grit size but decrease with high applied static load. The reported coolant types have no significant effect on MRR and surface roughness but provide better performance at certain pressure.

Wear occurs on both the end face and lateral face of the tool in RUM of advanced ceramics. The tool wear in terms of the diamond grain dislodgment on the end face is more serious than the lateral face. Mechanical impact and high temperature may contribute to the weakening of the interfaces between diamond grains and metal bond. Edge chipping is unavoidable phenomena in drilling hard and brittle materials but the edge chipping thickness could be decreased by increasing the support length.

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